New heart failure affects 500,000 Americans yearly. Nearly 50% of these patients have a normal left ventricular ejection fraction (LVEF) or so-called diastolic heart failure (DHF). New onset symptomatic DHF is a lethal disease with a 5-year mortality that approaches 50%.1 Echo-Doppler techniques use LV filling patterns and tissue Doppler imaging of the mitral annulus to help identify and classify the degree of LV diastolic dysfunction, but work best in symptomatic patients with advanced disease.2 Therefore, the diagnosis of early diastolic dysfunction, when asymptomatic and most treatable, remains problematic. A detailed causality-based, mechanistic understanding of what causes DHF, and how to most easily detect it, remains one of the most important unsolved problems in cardiovascular physiology and clinical cardiology.3

The Role of Left Atrial Function in Diastolic Heart Failure

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The Present Study

To that end in this issue Kurt et al8 seek to advance our knowledge of additional clinical, anatomic and physiological correlates of DHF, with a particular focus on LA “diastolic function” and LA stiffness. They report clinical and echo-Doppler data on 64 subjects undergoing right heart catheterization with simultaneous echocardiography, and a control group of 27 control subjects. The 64 subjects included 25 with systolic heart failure (LVEF<50%), 20 with DHF and normal LVEF and 19 with LV hypertrophy from hypertension. The present study also included asymptomatic patients with advanced disease.2 Therefore, the diagnosis of early diastolic dysfunction, when asymptomatic and most treatable, remains problematic. A detailed causality-based, mechanistic understanding of what causes DHF, and how to most easily detect it, remains one of the most important unsolved problems in cardiovascular physiology and clinical cardiology.3

The online-only Data Supplement is available at http://circimaging.ahajournals.org/cgi/content/full/2/1/6/DC1.

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(Circ Cardiovasc Imaging. 2009;2:6-9.)
© 2009 American Heart Association, Inc.
Circ Cardiovasc Imaging is available at http://circimaging.ahajournals.org
DOI: 10.1161/CIRCIMAGING.108.845503

The Constant Volume Heart

The normal 4-chambered heart (the contents of the pericardial sac) is, within about 5%, a constant volume pump throughout the cardiac cycle9 that is anchored posteriorly in the area of the pulmonary veins, and anteriorly by the junction of the sternum and the diaphragm. The long axis dimension (from apex to pulmonary veins) of the 4-chambered heart remains fixed throughout the cardiac cycle (see accompanying MRI cine loop of the normal heart in 4-chamber [Movie 1] and parasternal long axis views [Movie 2]). A small 5% deficit in volume occurs in systole as a result
of slight radial displacement (crescent effect) of the epicardial surface and is replenished by filling in early diastole as represented by the pulmonary vein D-wave. This replenishment generates the conduit volume of the left atrium. In contrast to the epicardial surface, the endocardium in systole undergoes significant radial displacement and the mitral and tricuspid annuli descend. This stretches both atria so that atrial and ventricular volumes reciprocate whereas total cardiac volume remains nearly constant (see Movie 1).

Clearly, in systole the ventricles are the energy source and the atria the recipient of this work. This is also true in early diastole when ventricular relaxation and elastic recoil results in rapid ventricular filling (Doppler E-wave), movement of the mitral and tricuspid annuli upward and return of the atrial walls to their diastatic (equilibrium) state with a smaller volume. Only during the concluding portion of ventricular diastole, when atrial systole generates the Doppler A-wave, is the atrium an active energy source contracting and pulling the ventricles upward. All of the above kinematic relations can be easily appreciated by examination of cardiac MRI cine loops of normal adult hearts obtained in the usual, 4-chamber, parasternal long-axis, and short axis views (see Movies 1 and 2).

If the left ventricle is a large energy source, and the left atrium a small one that acts only briefly, and both chambers (but largely the ventricle) are constantly affecting the behavior of each other in a reciprocal fashion, is there a good time to study inherent atrial properties? Yes, most logically it would be during diastasis. There is no transmitral flow, there is no wall motion, and the atrium and the ventricle form a single chamber at the same pressure and at a fixed volume (see left ventricular angiogram, Movie 3). Diastasis defines the LV equilibrium volume, and by the constant volume attribute of the heart, diastatic atrial volume is the volume of the atrium at diastasis, when the atrium an active energy source contracting and pulling the ventricles upward and distends the LV while it simultaneously displaces a passive spring a unit length. Physiologically it is represented by the pulmonary vein D-wave. This replenishment results in rapid ventricular filling (Doppler E-wave), movement of the mitral and tricuspid annulus upward and distends the LV while it simultaneously generates retrograde flow into the pulmonary veins. As discussed with LAEF it is confounded by both LV and pulmonary properties.

**Hemodynamic Measurements**

Pulmonary wedge pressure is an estimate of phase lagged LA pressure, in the presence of normal pulmonary vascular resistance. Viewing pulmonary wedge pressure as a time averaged (and slightly offset) analogue of mean LA pressure is appropriate. The factors that determine mean LAP (assuming all valves are normal) are multiple and include volume status, LV systolic and diastolic function, as well as preload and afterload. Hence, pulmonary wedge pressure is only partially determined by intrinsic LA function.

**Left Atrial Ejection Fraction**

LA ejection fraction is defined as ([LA pre-A Volume]−[minimum LA volume])/pre-A volume. LA pre-A volume is the volume of the atrium at diastasis, when the ventricle is also at its equilibrium volume. In light of the (near) constant volume attribute of the heart, diastatic atrial volume is determined by 4-chamber interactions. However, among all the variables considered for LA function characterization, this static measure of volume is the one least confounded by other dynamic variables. Minimum LA volume at the end of the A-wave is determined by a combination of intrinsic LA contractility, and the load the contracting atrial myocardium faces. This load consists of passive LV properties (and 4-chamber heart coupling) and pulmonary capacitance since retrograde flow occurs backward into the pulmonary veins. As can be surmised, each term in the algebraic expression for LAEF is confounded by these numerous variables.

**LA Strain and Strain Rate**

These measurements by echo-Doppler technique are provided in units of % strain or % strain/second. The definition of strain is change in length per unit length; strain rate is the temporal derivative of strain. These measurements are usually obtained during ventricular and atrial systole using sample volumes placed in the atrial myocardium near but clearly superior to the mitral annulus. For LA “diastolic” strain variables (during LV systole) the source of the strain is the ventricle doing external work on the atrium as the LV ejects blood into the aorta. The amount and rate of strain measured is determined primarily by ventricular and LV afterload attributes, although it follows that passive atrial tissue properties—on which the LV is also doing work, also play a role. That LA strain in early diastole must be strongly influenced by LV systolic function is in accordance with the constant volume requirement that atrial and ventricular volumes simultaneously reciprocate. This physiologic principle is underscored in the current work by Kurt et al8 by the observation that: “LV stroke volume was significantly related to LA_E strain, such that patients with higher LA_E strain exhibited higher stroke volumes (r=0.35, P=0.04).”

LA strain with LA contraction is a measure of LA systolic function relative to the load the LA faces as it pulls the mitral annulus upward and distends the LV while it simultaneously generates retrograde flow into the pulmonary veins. As discussed with LAEF it is confounded by both LV and pulmonary properties.

**LA Stiffness**

Stiffness is conventionally defined as the force required to displace a passive spring a unit length. Physiologically it is the change in pressure required to increase the volume of a passive container a unit amount. The units of strain in physiology are mm Hg/mL. In the current study “the ratio of pulmonary wedge pressure to LA systolic strain was used to estimate LA stiffness.” LA systolic strain was determined by averaging values from four sites in the LA myocardium. This measure of LA stiffness has units of mm Hg, rather than mm Hg/mL. Although this does not have the units of conventional stiffness it is a reasonable analogue. Importantly, the denominator in this expression, although measured in the LA wall, is determined primarily by longitudinal,
apically directed displacement of the mitral annulus by the contracting ventricle, whereas the posterior aspect of the LA remains fixed. (Recall reciprocation of LA/LV volumes required by constant volume attribute—see 4-chamber MRI cine loops). Hence this index, usually attributed to the LA as a stiffness measure, is very strongly influenced by LV properties. The noninvasive analog of LA stiffness as \([E/e’]/LA_S\) was also reported. The fact that \(E/e’\) is related to LVEDP in the context of the constant volume heart has been derived from first principles\(^{18}\) and underscores the extent to which LV-LA coupling in diastole plays an important role.

To underscore the limitations of viewing LA strain during LV systole and LA stiffness as atrial properties—consider the physiologically symmetrical measurement of placing the Doppler sample volume for strain measurement in the LV wall, just below the mitral annulus during atrial systole. A peak strain and strain rate and stiffness for the LV can be measured but are clearly a consequence of atrial systole pulling up on the mitral annulus and ventricular myocardium. Labeling the obtained values as “LV diastolic function indexes,” because they occur during LV diastole, when they are caused by the work of LA systole, has obvious limitations.

### Concluding Remarks

The primary energy source, the left ventricle, plays a central role in the various static and dynamic relationships between the left atrium and left ventricle, and hence will markedly influence any parameters used to characterize LA function. Thus, caution is appropriate about the extent to which the current study “examine[d] the contribution of LA diastolic dysfunction to the development of DHF.” Rather, the data presented further implicate the LV as a key determinant of the factors that lead to DHF with preserved LVEF. Nevertheless, the authors are to be commended for their consideration of LA diastolic function as a possible etiologic determinant of DHF, their selection of groups, the use of simultaneous echocardiography and catheterization data and their use of newer indices such as LA strain and LA stiffness.

Because of its increasing clinical importance DHF in patients with normal LVEF will remain a field of intense scrutiny and clinical relevance. Further advances in the use of noninvasive imaging (echocardiography, cardiac MRI, cine-CT) complemented by modeling of atrial-ventricular coupling in the context of the constant-volume attribute may help identify intrinsic LA properties that may be contributors to the development of DHF. It is also conceivable that as computer models of LV, 2-chamber and 4-chamber heart function become more tractable\(^{16–19}\) new physiological relations will be found that more fully characterize the role of intrinsic LA function in DHF. Ultimately, imaging and modeling in synergy, which includes the arterial system,\(^{20}\) will lead to earlier diagnosis of DHF and implementation of therapy. Although skeptics remain whether diastolic function is the primary disorder in DHF,\(^{21}\) and the role of atrial remodeling and dysfunction has been considered,\(^{22}\) continued investigation at the cellular and molecular level will help determine the ultimate causes of changes in LV structure and function that result in DHF.\(^{3}\)

### Acknowledgments

We gratefully acknowledge that the movies were provided by the cardiac MRI and catheterization laboratories in the Department of Medicine, Cardiovascular Division.

### Sources of Funding

Dr Appleton is supported in part by the Reid-Family Trust. Dr Kovács is supported in part by Barnes-Jewish Hospital Foundation and Alan A. and Edith Wolff Charitable Trust.

### Disclosures

None.

### References


Key Words: editorials • heart failure • left atrial diastolic function
The Role of Left Atrial Function in Diastolic Heart Failure
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doi: 10.1161/CIRCIMAGING.108.845503

_Circulation: Cardiovascular Imaging_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-9651. Online ISSN: 1942-0080

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Supplemental Data

Movie 1: MRI cine loop of the normal heart in 4-chamber
Movies 2 and 3: Parasternal long axis views